# Detection of Slow Magnetic Monopole

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### Abstract

*Numerous and all unsuccessful attempts of experimental search for monopole in cosmic rays and on accelerators in high energy particle collisions have been done since the possibility of existence of a magnetic monopole has been surveyed in 1931. Also the searches have been carried out in mica for monopole tracks as well as for relict monopoles, entrapped by ferromagnetic inclusions in iron-ores, moon rock and meteorites.*

*A new method of search for supermassive cosmic and relict monopoles by magnetically ordered film is considered. This approach resembles the traditional method of nuclear emulsion chamber. Apparently the proposed method is particularly attractive for detection of relict monopoles, released from melting iron ore.*

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# Contents

# 1 Introduction

A concept of a magnetic monopole has been introduced into modern physics in 1931 by Paul Dirac [1]. He postulated existence of an isolated magnetic charge $g$. Using general principles of quantum mechanics, he has related the electric and magnetic charge values: $ge = \frac{n}{2}\hbar c$, where $e$ is the electron electric charge, $\hbar$ is the Plank constant, $c$ is the speed of light, $n = \pm 1, 2...$ is an integer. Numerous but unsuccessful attempts of experimental search for these magnetic monopoles at accelerators and in cosmic rays have been done since then[2, 3, 4, 5].

The new interest to this problem has arised in 1974, when Polyakov [6] and 't Hooft [7] have shown that such objects exist as solutions in a wide class of models with spontaneously broken symmetry .

The magnetic charge of the Polyakov—'t Hooft monopole is a multiple of the Dirac one $g = 2ne/\alpha$, and the value of its mass $M_g$ lies in the range of $10^8$ — $10^{16}$ GeV. Such GUT's monopoles are not point-like and have complex structure

It is completely clear, that the Polyakov—'t Hooft massive monopoles can not emerge at accelerators, therefore we do not consider accelerator experiments. Moreover, we assume that the monopoles that reach the surface of the Earth are gravitationally bound up either with the Galaxy (if $\beta = v/c < 10^{-3}$) or with the Sun (when $\beta < 10^{-4}$).

The monopole ionization loss in matter has been evaluated by many authors (look at the reviews: [2, 3, 8]). For fast monopole the ionization loss appreciably (about 4700 times!) exceeds the loss for the minimum ionizing particles — MIPs, which is $dE/dl \simeq 2\ MeV/g$.

In units of the ionizing loss of particle with charge e, the monopole ionization loss is given by:

$$\left(\frac{dE}{dl}\right)_g = \left(\frac{dE}{dl}\right)_e \left(\frac{g}{e}\right)^2 \beta^2 \ . \tag{1}$$

If we recollect that ionization loss of a charged particle is proportional to $1/\beta^2$, then it is clear, that the loss of a monopole does not depend on velocity. It should be pointed out here that in GUT the monopole is a very heavy particle. **Therefore supermassive monopole is practically always non-relativistic!**

When $\beta \sim 10^{-3}$ the ionization loss of a monopole decreases to level of energy loss of MIP. At $\beta < 10^{-4}$ the ionization mechanism of the energy loss is switched off practically, because in this case the energy of monopole-atom collision already is not enough for ionization of the latter.

To estimate the maximum of monopole velocity $v$, it is natural to take the velocity of the Sun relatively to the background radiation

$$\beta = \frac{v}{c} \simeq 10^{-3} \ . \tag{2}$$

We shall remind here, that the virial velocity for our Galaxy does not exceed $10^{-3}c$ too.

For detection of a slow monopole with efficiency close to 1, the superconducting induction detectors were designed and constructed[9]. The single event, registered by the Cabrera detector, has originated the burst of experimental activity of searches for monopoles of cosmic origin. However, the significant progress in sensitivity (and corresponding limits on the monopole flux) has been achieved only for ionizing detectors [2, 10]. Sensitivity of these detectors is close to extended Parker bound [11]:

$$\mathcal{F} \leq 1 \cdot 10^{-16}(m/10^{17}\ GeV)\ cm^{-2}s^{-1}\ sr^{-1}.$$

One of the primary aims of the MACRO detector at the Gran Sasso underground lab (in Italy, at an average depth of 3700 hg/cm$^2$) is the search for magnetic monopoles for a large range of velocities at a sensitivity level well below the Parker bound for a large range of velocities, $4 \cdot 10^{-5} < \beta < 1$, $\beta = v/c$. MACRO uses three different types of detectors: liquid scintillators, limited streamer tubes and nuclear track detectors (CR39 and Lexan) arranged in a modular structure of six "supermodules". They consider magnetic monopole with enough kinetic energy to traverse the Earth $4 \cdot 10^{-5} < \beta < 1$, $\beta = v/c$. [13]

Another possibility of detection of a slow GUT's monopole is the search for proton decay induced by a heavy monopole [14], [15]. Recently the group working with the Baikal lake Cherenkov detector [16] has set the following limit on the flux of heavy magnetic monopoles and the Q-balls, which are able to induce the proton decay

$$\mathcal{F} < 3.9 \cdot 10^{-16} cm^{-2}s^{-1}sr^{-1}.$$

Here we consider a possibility of building-up of a new type of detector of slow monopoles. Our idea is based on registration of interaction of a slow cosmic-ray-related monopole with the film of easy-axis and high coercitivity ferromagnet. As a sensitive element of such a detector one can use an advanced storage media, namely – the magneto-optical disk (MO disk) [17]. (To our knowledge – for modern MO disks an areal density of $45\ Gbit/in^2$ has been demonstrated using near-field techniques, with a theoretical possibility in excess of $100\ Gbit/in^2$). The slow monopole which is passing through the magnetic coat of MO disk, leaves a distinctive magnetic track, and this track can be detected. It is important to note that considerable surface can be covered by MO disks. They can be exposed any reasonable time without any maintenance, like in emulsion chamber experiments or the CR39 nuclear track subdetector of MACRO [18].

Apparently, the use of such passive detectors will be especially effective in search of the relict monopoles, entrapped in ferromagnetic inclusions of iron ore. Such monopoles should be extracted from the ore during the melting process. These monopoles are extracted at relatively small cross-section of the furnace and freely fall downward. Such slow moving monopoles can be detected by a passive detector with MO disks. These disks are to be placed, e.g. in a cavity under the furnace. The effective exposition time, normalized to the mass of ore, from which the monopoles are extracted, can be very large. We wish note, that during the exposure no detector service is required. After exposure the MO disks should further be placed into specialized device to find the traces of the magnetic monopole. Ours real, but for the future aim consists in study of a possibility of making of such specialized device.

## 2   Track formation by the slowly moving monopole.

It is expected that a slow monopole, moving transversely through a magnetized ferromagnetic film, should leave a distinctive track of magnetization in it. We can use this

phenomenon to design an effective detector of supermassive cosmic monopoles. For this purpose we shall consider in detail the mechanism of magnetic track formation by such a type of monopoles [19, 20].

Let us consider a thin layer of easy-axis hard ferromagnetic magnetized perpendicularly to the surface along an easy axis. It is easy to see that the external magnetic field is absent (double layer!), but the surface density of a magnetostatic energy of such configuration is rather large. However, if the anisotropy constant $K_u$ is reasonably large, and the effective field of anisotropy exceeds the value of demagnetizing field then the system is in a metastable state. As film magnetization is inversed in a small area, a stable cylindrical domain (magnetic bubble) of certain radius is created. Such one domain state is characterized by an equilibrium radius $r_{eq}$ and a collapse radius $r_c$ where $r_{eq} > r_c$. As the domain radius is decreasing and approaching to the collapse one, $r_c$, the magnetic bubble becomes unstable and disappears. A typical magnetic bubble size is about 30 nm for film thickness of 100 nm.

What is the field of a monopole at such distance?

$$H = \frac{\Phi_0}{4\pi r_0^2} \simeq 2 \cdot 10^3 \ Oe \ , \tag{3}$$

that is enough without any doubt for re-magnetization of a material with coercitivity of the order of 1 Oe. We have introduced here some characteristic radius

$$r_0 = 2\mu_0 \gamma / I_s^2$$

which defines the minimal radius of collapse.

All above-mentioned is true for films with high mobility of domain walls. Films with low wall mobility are even more stable, and at the same time, domains with radius less than the collapse radius can exist in them, in principle. So, in the $Co/Pt$ films the movement of domain walls is suppressed. And in the 20 nm film the transverse domains of cylindrical form with diameter of the order of 50-100 nm are obtained. Let us note, that the coercitivity of the easy-axis $Co/Pt$ film is of the order of 1-2 kOe [21].

However, our speculations are true only in static, for very slow monopoles only. As we have noted before, the characteristic velocity of a monopole is $v \simeq 10^{-4} - 10^{-3}c$, and for our consideration let us assume $v = 10^{-4}c$. The time of monopole interaction with an electron $\tau$ can be defined as the time, during which a field higher than some critical field $H_c$ interacts with the electron

$$\tau \simeq \frac{r_c}{v} \simeq \frac{1}{v}\sqrt{\frac{\Phi_0}{4\pi H_c}} \ . \tag{4}$$

At $H_c$ of the order $3 \cdot 10^3$ Oe we have $\tau \sim 3 \cdot 10^{-12}$ s. It means, that the spin flip of the magnetic in the "track" takes place during the interaction time.

For such spin flip, the adiabatic condition is necessary — the frequency of spin precession in the overturning field should be much larger than the inverse time of the interaction

$$\omega = \frac{\mu_B H}{\hbar} \gg \frac{1}{\tau} \ . \tag{5}$$

It is possible to derive from here the minimal magnetic field which is appropriate for the adiabatic mode, and the track radius:

$$H \gg H_c = \frac{\hbar}{\mu_B \tau} = \frac{4\pi \hbar^2 v^2}{\mu_b^2 \Phi_0} \ , \tag{6}$$

$$R_t \ll r_c = \sqrt{\frac{\Phi_0}{4\pi H_c}} \; . \tag{7}$$

In our case at $v \simeq 10^{-4}c$ we get

$$H_c \simeq 10^7 Oe \; ; \quad r_c \simeq 10^{-7} cm,$$

and for $v \simeq 10^{-6}c$, we have

$$H_c \simeq 10^3 Oe \; ; \quad r_c \simeq 10^{-5} cm.$$

It is obvious, that the conditions of adiabatic and even resonant spin flip are not fulfilled, while $r_c < r_0$, that corresponds to the monopole speed $v \simeq 10^{-6}c$.

We shall consider the influence of the conductivity of the film material now. The reason is that the monopole magnetic flux is being frozen into the cylindrical area around the track axis and then spreads radially. The radius of the flux pipe and the diffusion factor of the flux are determined by the film conductivity. The radius of the flux pipe $\delta_c$, we can find:

$$\delta_c = \frac{c^2}{2\pi \cdot \sigma \mu v} \; . \tag{8}$$

This length has a simple physical meaning. At distances less than $\delta_c$ the monopole field can be considered as free. At distances of the order of $\delta_c$ and more, the magnetic tail of the monopole is formed, which is an analogue of a string in a superconductor. Due to the finite conductivity of material, the tail spreads gradually, and the energy of the magnetic field converts into heat.

At the monopole velocity about $v \simeq 10^{-4}c$, the flux pipe has the radius of the order of $10^{-5} cm$. The flux pipe spreads in time as:

$$R(t) = \delta_c \sqrt{\frac{t}{\tau}} \; . \tag{9}$$

Thus the magnetic moment of the track is conserved, as well as the frozen flux. It is easy to calculate the average intensity of the magnetic field in the flux pipe immediately after monopole flight

$$H = \frac{\Phi_0}{\pi \delta_c^2} \sim 10^3 Oe \; . \tag{10}$$

The typical time of the monopole interaction with an electron in a conductor is:

$$\tau \simeq \frac{\delta_c}{v} \simeq 10^{-11} - 10^{-10} \; s \; , \tag{11}$$

and the field strength, providing the adiabatic inversion of the magnetic spin in a track, will be:

$$H_c \simeq \frac{\hbar}{\mu_B \tau} \simeq 10^4 \; Oe \; . \tag{12}$$

Thus, the frozen field in the conductor $H_c$ can effect appreciably the process of spin flip in the track and provide the adiabatic spin flip of electrons in the magnetic at monopole speeds below $10^{-4} \; c$.

# 3  Detection of the monopole track.

As it was shown, the domain induced by the moving monopole has the typical size of the order of 50 nm and magnetization about several thousand Gauss. Then the domain magnetic flux $\Phi_d$ will be of the order: $\Phi_d = \pi r^2 \cdot I_s \simeq \Phi_0 = 2 \cdot 10^{-7} \ G \cdot cm^2$

For detection of such a flux we can use the high sensitive fluxmeter on the basis of superconducting quantum interference device — SQUID, or magneto-optical device on the basis of Kerr effect (rotation of the polarization plane of light reflected by a surface of a ferromagnet which is magnetized perpendicular to the surface). It is clear that the second way is technically easier and does not require a cryogenic maintenance. In the later case, the realization of such a detector requires a surface covered with a thin layer of easy-axis magnetized magnetic media, plus a magnetooptic device to detect the spots of transverse magnetization of the film (to detect the domain of opposite direction of magnetization!) with a system of precise positioning.

A similar technique has emerged recently in an almost ready shape, suitable for the detector design with minimal adjustment. It is the magneto-optic recording technology used in modern magneto-optic disks (MO disks) and their readout devices. Already there are MO disks with multilayer coating of $Sm/Co$ and $Pt/Co$. The coercitivity of multilayer coats $Pt/Co$ is about 1 $KOe$ at 10 layers of total thickness about 15 $nm$ [21]. The size of a magnetic bubble which can be detected in such a coat by the magneto-optical method is about 60 $nm$. This technique using the near-field optics has been designed, f.i. in Bell Laboratories [22].

The coercitivity of coats with $Sm/Co$ is in the interval $3-5 \ kOe$, and the reference size of magnetic bubble is 50 $nm$ [21]. For detection of the magnetic track of the monopole it is possible to use slightly modified standard MO-drives. Having covered a large enough surface with such MO disks, we can obtain an effective and relatively nonexpensive detector of slow moving space monopoles, which we can expose during unlimited time.

However, it is more effective to use the MO-detector to search for relict monopoles, entrapped in ferromagnetic inclusions of iron ore. Naturally, the melted iron ore becomes paramagnetic and the ferromagnetic traps disappears. Then the monopole is likely to be surrounded by a cluster of several dozens of iron atoms. The size of a complex is determined by thermodynamic equilibrium:

$$\frac{\mu_{Fe} \cdot g}{r_{Fe}^2} = \frac{3}{2}kT \tag{13}$$

The radius of the iron atomic complex paramagnetically bound to the monopole at $T \approx 1200^0 \ C$ is:

$$r_{Fe} \simeq 6 \cdot 10^{-8} cm. \tag{14}$$

Such complexes contains about 30 atoms of iron. Considering, that the movement of such small blob is determined by the Stokes law:

$$F_v = 6\pi \cdot r_{Fe} \cdot \eta v \ , \tag{15}$$

where $v$ is the monopole velocity, $\eta$ is the dynamic viscosity of liquid foundry iron, $\eta = 2 \cdot 10^{-3} kg/(m \cdot sec)$ at $T = 1250^0 \ C$.

Equating the force of friction to the gravity $F_g = mg$, we find the velocity $v$ of the monopole falling through the melt

$$v = \frac{mg}{6\pi \cdot r_{Fe} \cdot \eta} \ , \tag{16}$$

that makes $v \simeq 3 \cdot 10^{-1} m/sec$ for a monopole with mass about $10^{15}$ $GeV$.

This corresponds to kinetic energy of the complex about $10^6$ $eV$, which is large enough for a skinning off of the complex at the solid bottom of the furnace. Let's remark, that from a formal point such an approach is quite acceptable, as the Reynolds number in our case it is not large enough: $Re < 10^{-3}$.

This grain (complex) should sink in the liquid iron at 10-100 cm/s velocity until it reaches the bottom of the blast furnace. Then the atoms of iron are stripped off the monopole in the material of the oven bottom, and the monopole falls further, accelerating up to the velocity of sound in the matter.

We should have in mind, that the energy loss of monopole due to the Cherenkov radiation of phonons and magnons in a medium reach $10^8$ $eV/cm$ and even more, as it was shown earlier [19],[20]. This is a main point to understand, that the gravitation forces cannot accelerate the monopole up to velocity higher than the speed of sound in a medium.

Usually the blast furnace melts about 10 000 tons of ore per day, and it is possible without great problems to expose the MO-detector, for example, during one year. Thus we hope that such MO-detector can improve significantly the experimental limit on the density of relict monopoles entrapped in iron ore, which today is equal to $\rho_m < 2 \cdot 10^{-7}/g$ [23].

Furthermore, in a sinter machine the ore is also heated above the Curie temperature, but not up to the melting point. So, to shake off the iron atoms, we have to kick the iron ore pieces with acceleration of $10 - 100$ $g$. Clearly, in this last case the probability of monopole release is considerably lower.

# 4 Conclusion.

The interaction of monopoles with films of magnetic materials is considered. In particular, the interaction of slow monopoles with thin films of easy-axis magnetics with high and low mobility of domain walls (materials with magnetic bubbles)is discussed. It is shown, that during the movement of a slow monopole through the magneto-hard magnetic film, a track-domain can be formed with typical size of about 50 nm and with magnetization of about several thousand Oe. Thus the magnetic flux of the track appears to be about the value of the flux quantum. For detection of such a flux, the detectors using fluxmeter on the basis of already widely known SQUID can be used.

It appears that for registration of traces of slow cosmic monopoles in magnetic matter, the experimental devices using the Kerr magneto-optical effect are more appropriate. They have emerged recently in a shape suitable for detector design, with an appropriate adjustment.

It should be realized that such passive detectors will be especially effective in search of relict monopoles, entrapped in ferromagnetic inclusions of iron ore. These monopoles should be extracted from the ore during melting process. Then these slow moving monopoles can be detected by a passive MO detector. We can expose MO disks in a cavity under a blast furnace exactly under the bath with melting metal, where the temperature does not exceed $+50^0$ $C$. In the melting process the temperature of ore exceeds the Curie point and its ferromagnetic properties disappear. Hence the ferromagnetic traps which hold the monopoles are "switched off" and the released monopoles fall through the melting metal to the bottom of the bath and finally through the MO disks. While a monopole, moved downward by the gravity force crosses the surface of one of the MO disks, it leaves a magnetic track in its coat. It is possible to obtain the slow moving relict

monopole also by the sinter machine, and usually both installations process no less than 10 000 tons of ore per day.

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